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Phosphorus Removal Within Existing Wastewater Treatment Facilities

Research Report No. 44

arch Program for the Abatement of Municipal Pollution
under Provisions of the Canada-Ontario Agreement
on Great Lakes Water Quality

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RESEARCH REPORTS

These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies carried out in this program through in-house projects by both Environment Canada and the Ontario Ministry of the Environment, and contracts with municipalities, research institutions and industrial organizations.

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Phosphorus removal within
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PHOSPHORUS REMOVAL WITHIN EXISTING WASTEWATER TREATMENT FACILITIES

by

Boris I. Boyko and J.W. Gerald Rupke
Ontario Ministry of the Environment

RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION WITHIN THE
PROVISIONS OF THE CANADA-ONTARIO
AGREEMENT ON GREAT LAKES WATER QUALITY

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ABSTRACT

The various projects reported herein were undertaken to assist in the implementation of the Province of Ontario's phosphorus control program. Under this five-year program, phosphorus removal was to be initiated on the discharges of more than 170 existing wastewater treatment plants serving some five million persons.

In order to implement this program, a methodology to predict the coagulant best suited for phosphorus removal at any particular treatment facility was required. It was also necessary to determine whether the chemicals used for phosphorus removal would have any physical or process effects on present wastewater treatment processes, facilities, methods of sludge treatment, and subsequent sludge disposal practices.

This report discusses coagulation prediction and prime coagulant selection, and the operational results, problems and design considerations derived from a series of full scale studies.

The study concluded that phosphorus removal may be readily implemented with minimal capital expenditure at operating municipal wastewater treatment facilities of all designs currently in use in Ontario.

RÉSUMÉ

Les divers travaux dont fait état le présent rapport visaient à faciliter l'amorce d'un programme quinquennal de la province d'Ontario s'attaquant au phosphore déversé dans les cours d'eau. Ce programme voulait réduire le taux de phosphore des effluents de plus de 170 usines de traitement des eaux usées servant une population de quelque cinq millions de personnes.

Dans un premier temps, on a élaboré des méthodes pour déterminer les coagulants les mieux appropriés à réduire le phosphore dans les différentes techniques de traitement. Dans un deuxième temps, on a tenté de déterminer l'influence des produits employés sur le déroulement ou le rendement des procédés ou des installations, sur les méthodes de traitement des boues, puis sur les modes d'élimination ultérieure de ces dernières.

Les rapport traite des prévisions des taux de coagulation, du choix du meilleur coagulant, des résultats du traitement et des difficultés de conception et d'application à la lumière des conclusions d'une série d'études très étendues.

En conclusion, on peut dire qu'il est possible de réduire considérablement les taux de phosphore avec des capitaux modestes dans tous les types d'usines traitant les eaux usées des municipalités ontariennes.

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PREFACE

This report is a compilation of the results obtained from a number of individual research projects conducted over the period April, 1971 to December, 1973. Only some of these projects were funded under the Canada-Ontario Agreement; those not were supported through internal funding from the Ministry of the Environment. The report specifically covers the following Canada-Ontario Agreement Projects conducted by the Research Branch of the Ministry of the Environment: 71-1-1, 71-1-2, 71-1-3, 71-1-4, 71-1-6, 71-1-9, 71-1-11 and 71-1-14.

These projects will not be reported individually elsewhere. More specific information concerning any one of the individual projects may, however, be obtained by writing to: Wastewater Treatment Section, Pollution Control Branch, Ontario Ministry of the Environment.

S.A. Black
Wastewater Treatment Section
Pollution Control Branch
Ontario Ministry of the Environment

1. INTRODUCTION

The Province of Ontario is presently involved in a five-year program to control phosphorus discharges from more than 170 existing wastewater treatment plants serving some five million persons. In order to implement this program, it was necessary to develop methodology that would allow prediction of the coagulant best suited for phosphorus removal at any particular treatment facility, and to determine whether the chemicals used for phosphorus removal would have any physical or process effects on present wastewater treatment processes, facilities, methods of sludge treatment, and subsequent sludge disposal practices.

A research program, funded under the Canada-Ontario Agreement on the Lower Great Lakes, was undertaken, using jar testing techniques for the predictive aspects of the study; full scale phosphorus removal studies were conducted at wastewater treatment facilities ranging in size from 0.05 to 24.0 mgd capacity.

This report discusses the predictive methodology, operational results, problem areas, and design considerations derived from the full scale studies conducted.

In addition, the results of studies involving phosphorus removal through batch treatment or continuous chemical addition to waste stabilization pond systems are discussed. Phosphorus removal using post-secondary treatment methods is also reviewed.

2. BACKGROUND

A report published by the International Joint Commission in 1969 [1] recommended that phosphorus discharges from all sources in the Lower Great Lakes be reduced to the lowest practical level. Subsequently, the Province of Ontario announced a policy requiring the installation of phosphorus removal facilities at municipal and institutional wastewater plants in the Lower Great Lakes area and on inland recreational waters.

Initially, the policy required a minimum removal of 80 percent of the phosphorus from wastewater plant influents, with the need for higher levels of removal to be determined by further studies of the receiving waters. This criterion was superseded in the Lower Great Lakes by the signing, in April, 1972, of the Canada-United States International Agreement on Great Lakes Water Quality [2], which called for an effluent objective of one mg/l total phosphorus.

Permanent phosphorus removal facilities were operational as of December 31, 1973 in the most critically affected areas of the Province, and were to be operational by December 31, 1975 for those discharging to waters deemed to be in a less critical condition, and three years after notification in all other areas of the Province where problems are found to exist. Figure 1 outlines the scheduled phosphorus removal compliance dates for the southern section of the Province of Ontario.

In order to implement and accelerate pollution control programs, the governments of Canada and Ontario signed an agreement [3] that secured funding for a $250,000,000 capital works program aimed at upgrading sewage collection systems and treatment works, and including the installation of phosphorus removal equipment. An additional $6,000,000 over the five-year term of the agreement was provided for related research studies.

Although considerable research effort had gone into earlier technical studies of phosphorus removal at wastewater treatment plants, the studies conducted by the Ministry of the Environment and funded by the Canada-Ontario Agreement, had the following objectives:

1) Develop methodology that would allow the prediction of the coagulant that would be best suited for phosphorus removal at a particular water pollution control plant (WPCP);

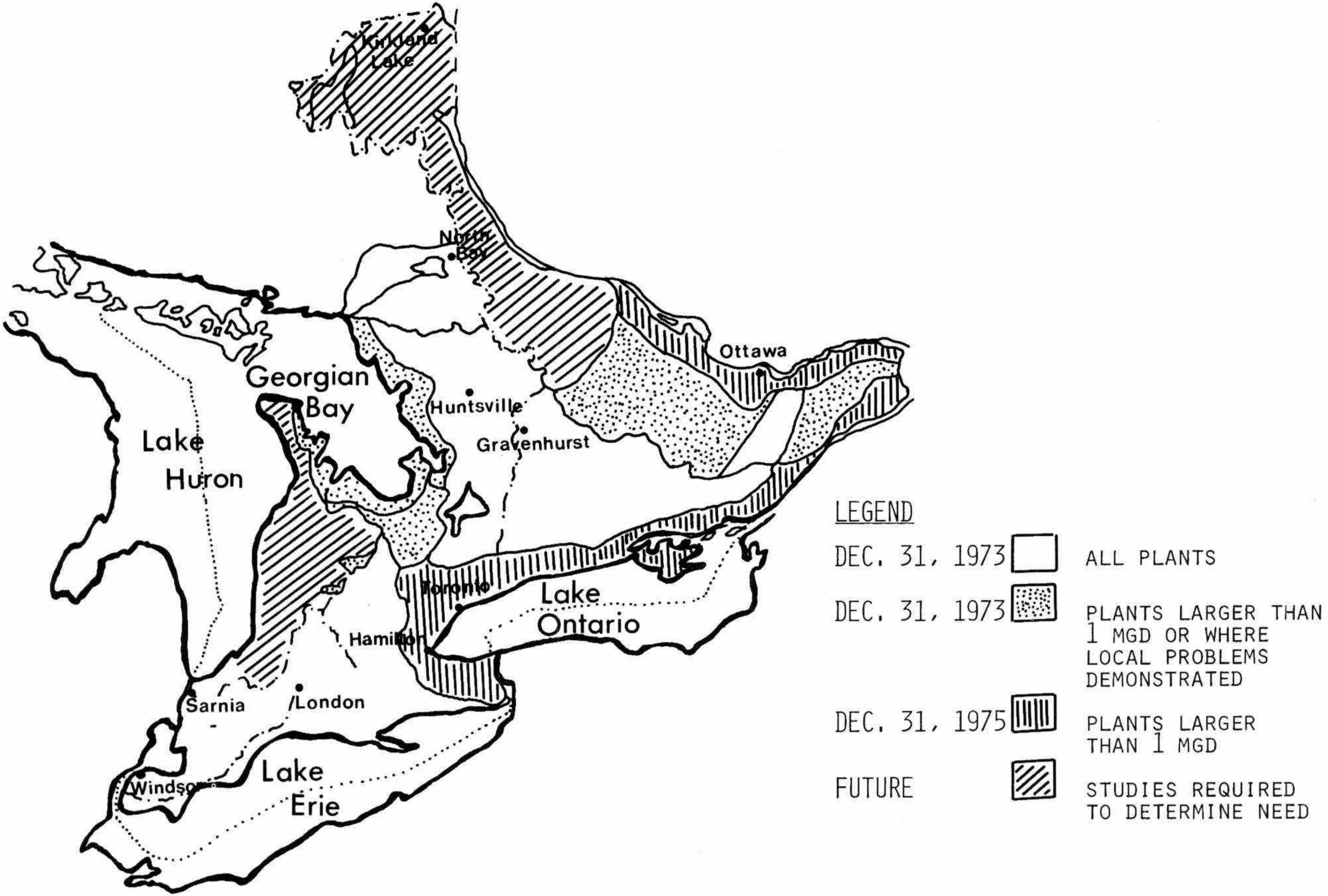
Kirkland Lake
North Bay
Ottawa
Georgian Bay
Huntsville
Gravenhurst
Lake Huron
Toronto
Lake Ontario
Hamilton
Sarnia
London
Windsor
Lake Erie
LEGEND
DEC. 31, 1973 ☐ ALL PLANTS
DEC. 31, 1973 ▒ PLANTS LARGER THAN 1 MGD OR WHERE LOCAL PROBLEMS DEMONSTRATED
DEC. 31, 1975 ▥ PLANTS LARGER THAN 1 MGD
FUTURE ▨ STUDIES REQUIRED TO DETERMINE NEED

FIGURE 1. PROVINCE OF ONTARIO - SOUTHERN SECTION

PHOSPHORUS REMOVAL PROGRAM SCHEDULED COMPLIANCE DATES

2) Determine the effects of phosphorus removal using prime coagulants on the activated sludge process and its major modifications;

3) Provide information on both the quantity and quality of sludge to be expected from WPCP's effecting phosphorus removal;

4) Ensure that the present methods of sludge treatment were adequate for chemical-organic sludges;

5) Determine whether phosphorus removal could be readily implemented into existing treatment plants without major capital works expenditures; and,

6) Provide a method of phosphorus removal in nonmechanical treatment systems, e.g. stabilization ponds and aerated lagoons.

3. TREATABILITY STUDIES

3.1 Predictive Methodology

3.1.1 Procedure

The use of jar testing procedures to simulate water treatment plant conditions is a well known and often used technique [4]. More recently, this same jar test procedure has been used to provide preliminary design information on phosphorus removal by chemical precipitation in municipal wastewater treatment systems. This standard procedure parallels that used by potable water treatment plant operators in that a standard arbitrary timing sequence is used to ensure adequate mixing, reaction, and sufficient flocculation. The specific details of the jar testing procedures used are available elsewhere [5]. Rather than attempting to duplicate hydraulic and mixing conditions within a particular WPCP being studied, a standard jar testing technique was adopted and yielded satisfactory predictive results.

The preliminary testing is done on both raw sewage and final effluent grab samples, using a wide range of primary coagulant dosages. Additional jar tests are subsequently conducted to narrow the range of coagulant dosage needed to effect the required degree of phosphorus removal, expressed either as a percentage removal or a residual phosphorus concentration.

Finally, a number of jar tests are performed using dosages which bracket the range of removal efficiency desired, i.e., dosages yielding removals lower, equal to, and higher than the objective. It is essential that these jar tests be conducted over an extended period of time in order that a representative variety of sewage characteristics are encountered. Grab samples for jar testing should be taken at different times of the day and on various days of the week. Once the range of chemical dosages has been determined, it is essential that the dosages used in the jar testing not be altered, in order to avoid deliberately skewing the results. In order to have sufficient data to draw meaningful conclusions, it was arbitrarily considered that a minimum of ten data points should be obtained for each chemical dosage on each waste stream being studied.

3.1.2 Data analysis

Rather than looking at the average total phosphorus removal for each set of data, more meaningful information can be obtained by plotting each set of data points on arithmetic probability paper. This allows a direct comparison of the various chemical dosages used.

Such probability curves have two significant characteristics:

1) The relative vertical position indicates the degree of effectiveness of the coagulant used at that given dosage.
2) The slope of the line indicates the expected reliability of phosphorus removal using that particular coagulant.

A typical set of data using alum as the coagulant on raw sewage is shown in Figure 2.

Using similar curves for each coagulant, the dosage requirements to yield a given degree of phosphorus removal (or residual phosphorus value), for a specified frequency, may be determined.

The relative economics of the chemical processes for total phosphorus removal can then be determined on the basis of optimum dosage, delivered cost, and availability of chemical.

3.1.3 Results and discussion

Graphic interpretation of the jar test data accumulated from many of the WPCP's tested to date is shown in Figures 3 - 7. Each figure represents the overall study results obtained using a particular coagulant on raw sewage (Figures 3 - 5), or on final effluent (Figures 6 - 7).

Each of the data points used in the regression analysis and confidence limit determination represents the complete result of the jar test study conducted at a particular WPCP and not an individual jar test result.

Since it has been previously speculated that coagulant demand to effect a specific phosphorus removal is a function of influent phosphorus concentration, Figures 3 - 7 are presented as coagulant dosage plotted against influent phosphorus concentration. Where jar

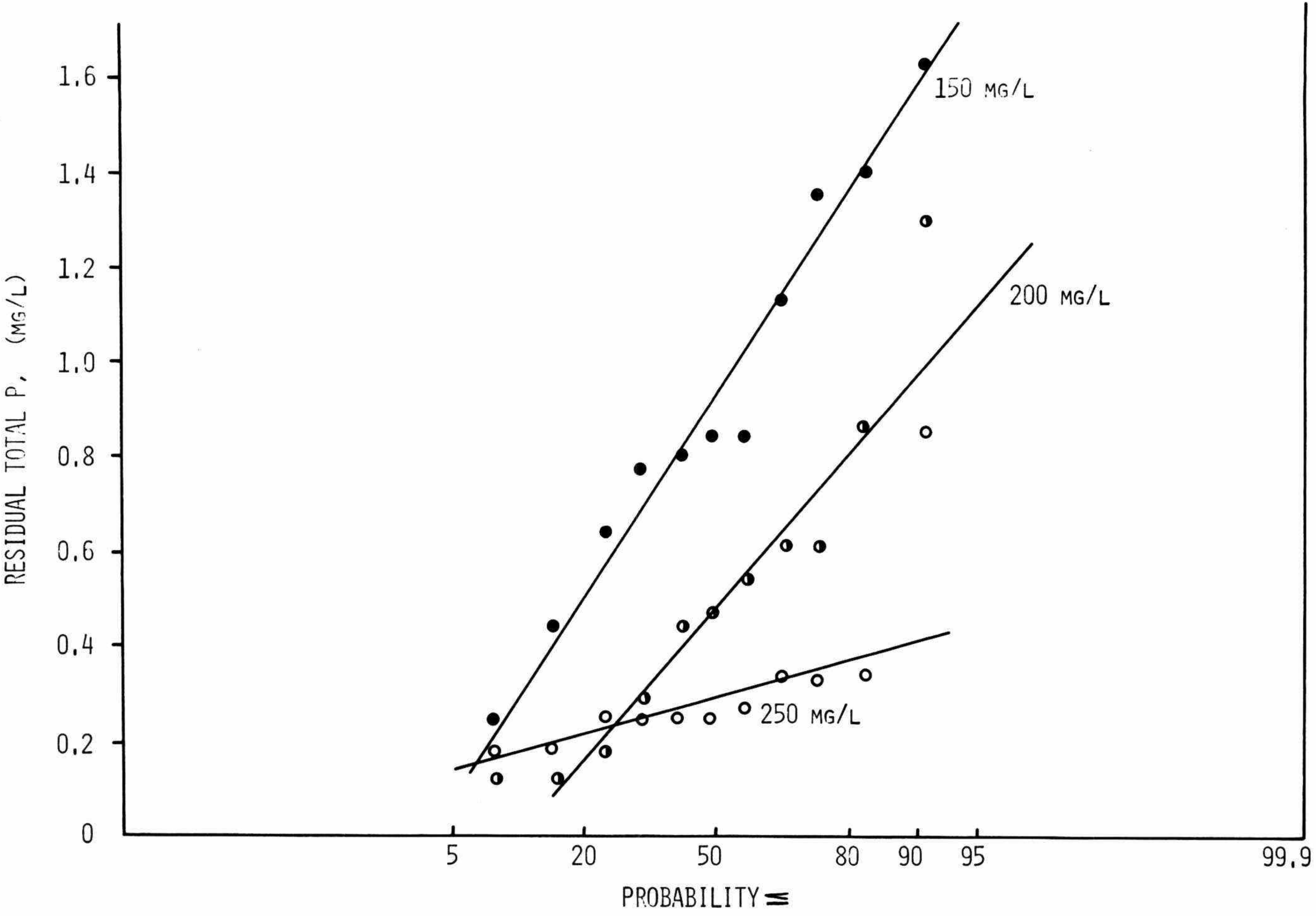

FIGURE 2. JAR TEST RESULTS, ALUM ON RAW SEWAGE

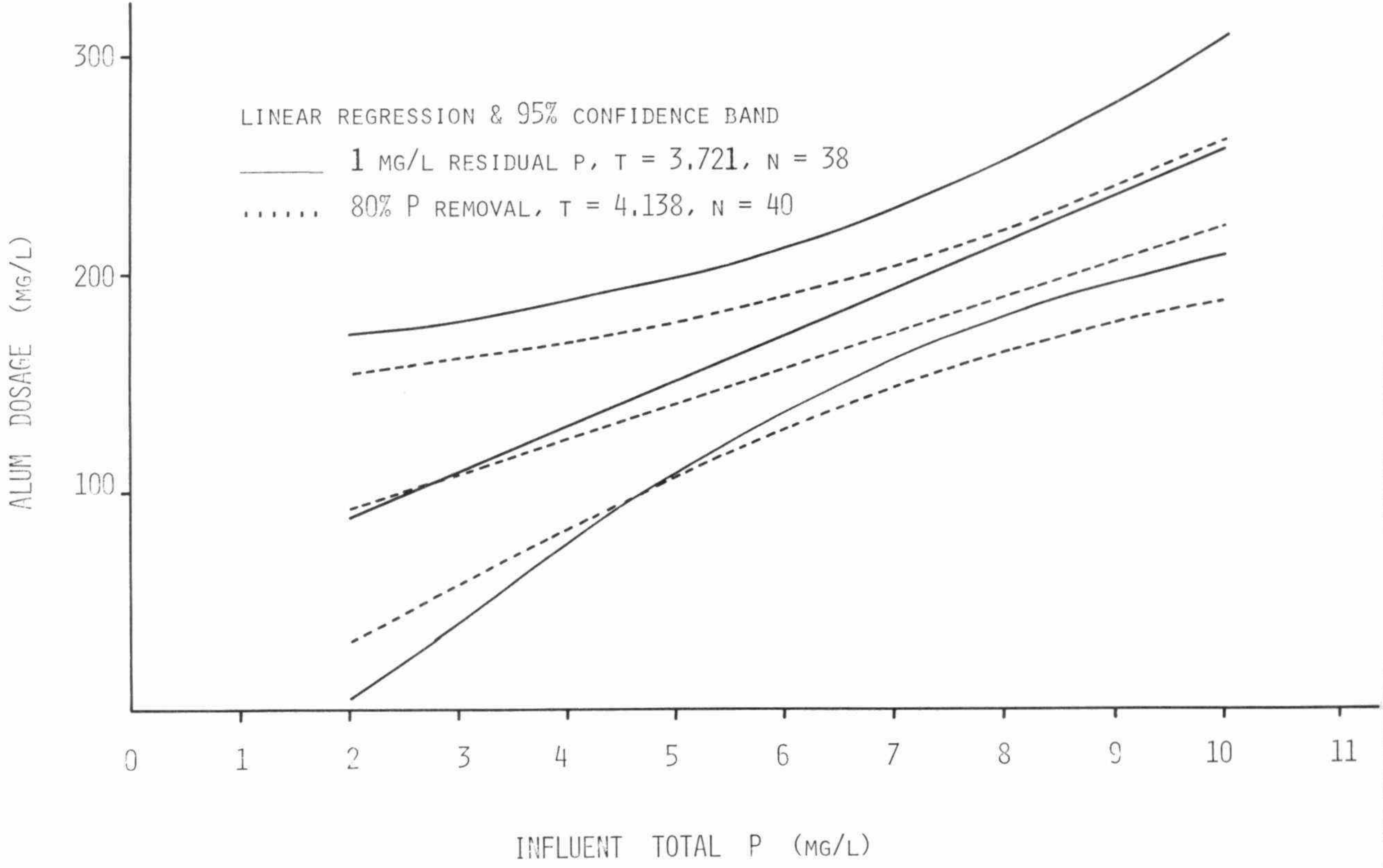

FIGURE 3. P REMOVAL IN RAW SEWAGE, ALUM DOSAGE VS TOTAL PHOSPHORUS

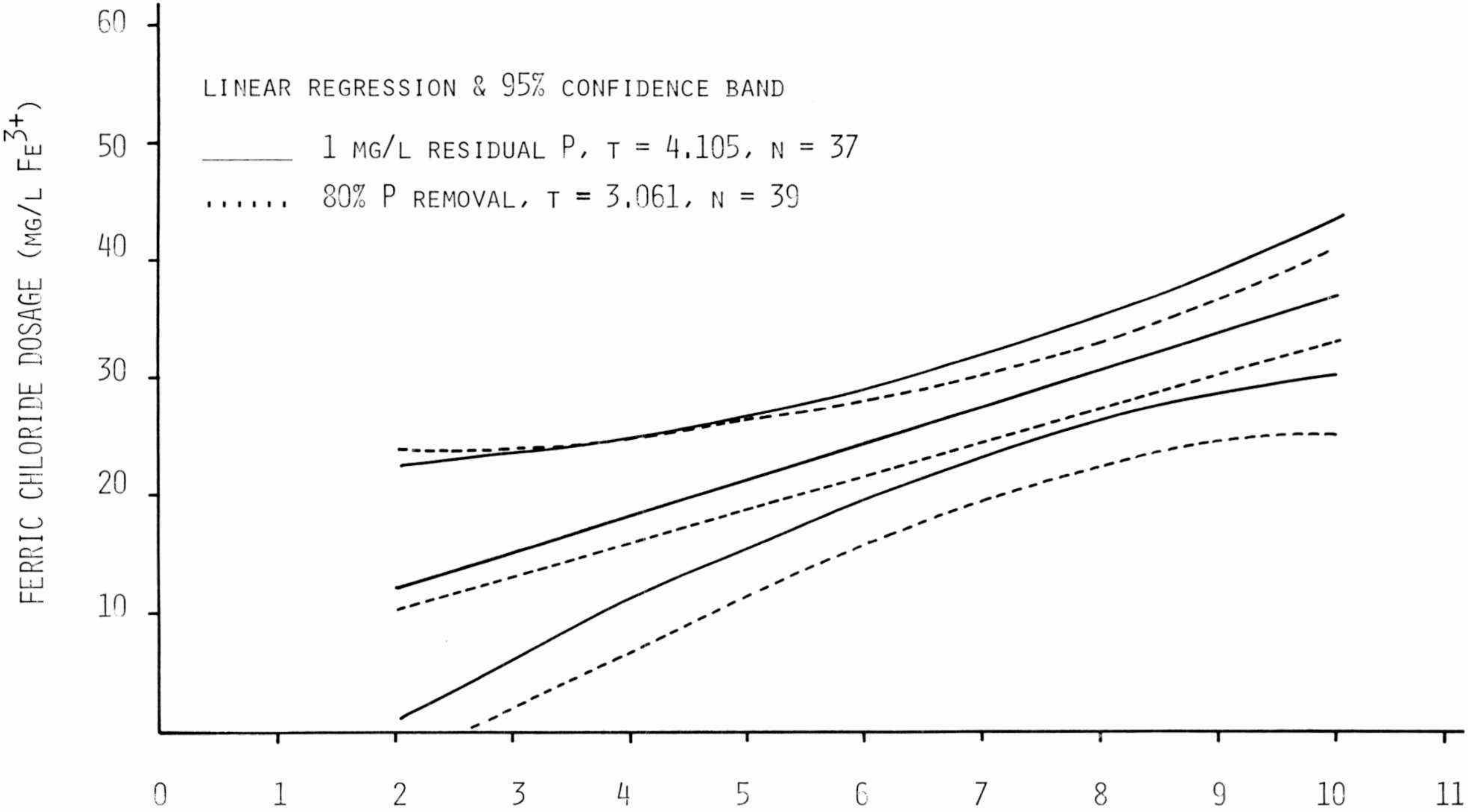

FIGURE 4. P REMOVAL IN RAW SEWAGE,
FERRIC CHLORIDE DOSAGE VS TOTAL PHOSPHORUS

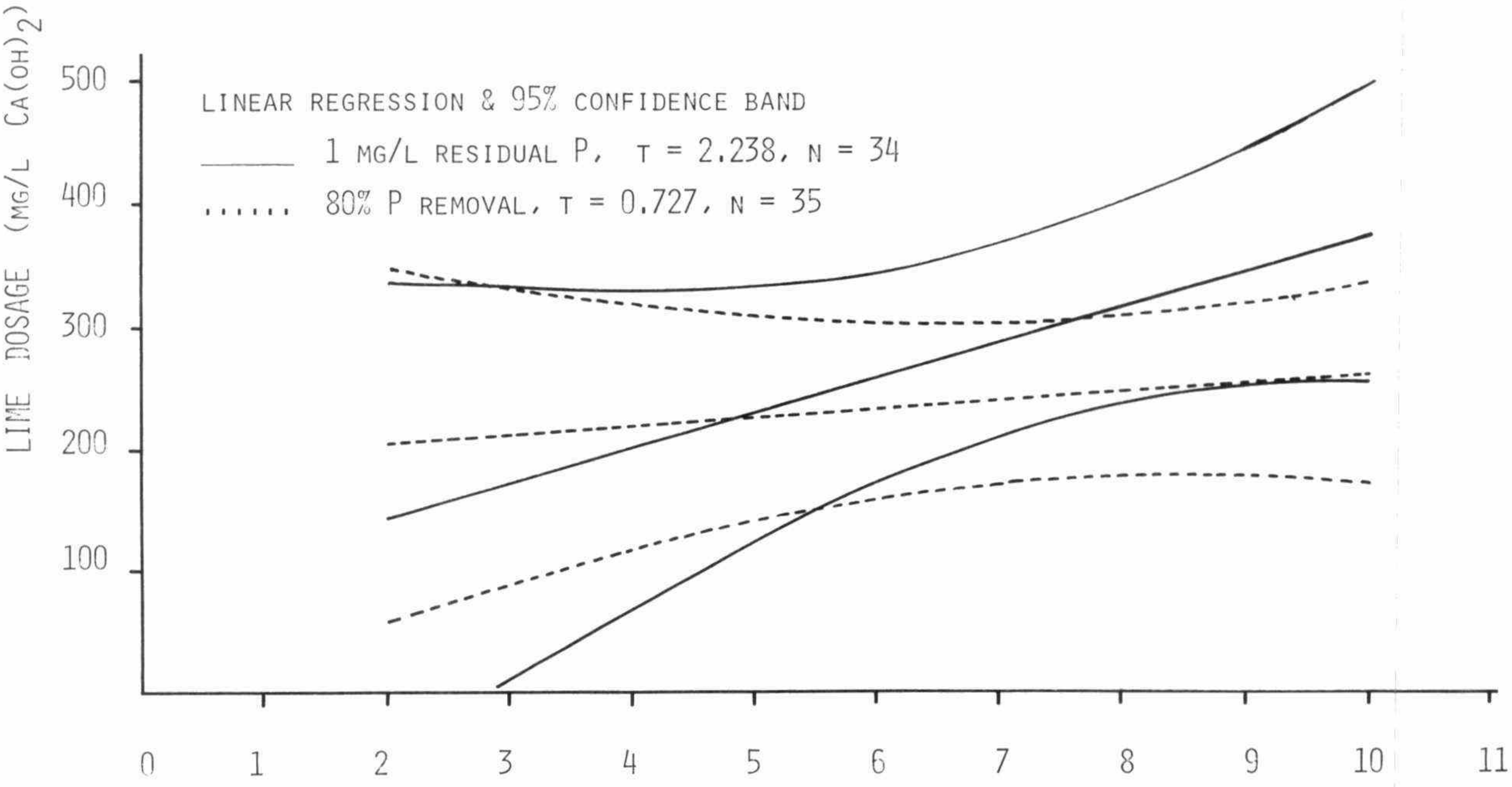

FIGURE 5. P REMOVAL IN RAW SEWAGE,
LIME DOSAGE VS TOTAL PHOSPHORUS

tests were conducted on final effluent, the coagulant requirement has been plotted against final effluent total phosphorus concentration.

From Figures 3, 4 and 5, all involving addition of prime coagulant to raw sewage, it can be seen that slightly higher dosages were required for 1 mg/l residual total phosphorus level, than for 80 percent reduction of raw sewage total phosphorus. Although the significance of correlations can be determined from the given t values, the wide 95 percent confidence band indicates that such a correlation, where it exists, is of little value for either predicative or control purposes. Figure 5 illustrates that, in order to effect 80 percent removal of raw sewage phosphorus, the required lime dosage was independent of raw sewage phosphorus concentration. When using lime for phosphorus removal, the degree of removal achieved is usually a function of the ultimate pH level attained. Chemical constituents other than phosphorus provide the major buffering action against changes in pH.

In Figures 6 and 7, the chemical requirements found to effect phosphorus removal using alum and ferric chloride on final effluent are shown. Studies conducted in the early part of this program indicated that jar tests done on final effluent gave similar results to those conducted on mixed liquor. This then allowed the use of final effluent for jar testing that would yield predictive results with respect to the application of coagulant into mixed liquor. This preliminary testing procedure does not take into account the effects of accumulated coagulant within the mixed liquor; full scale studies have been successful using somewhat lower dosages than those predicted by jar tests.

Figures 6 and 7 indicate that, in general, a reduced coagulant dosage was required to effect phosphorus removal in the aeration tank when compared to the addition of chemical to raw sewage.

Although it may be possible to eliminate one of the prime coagulants (lime) from the jar test study, depending on the type of wastewater treatment facility, jar tests should always be conducted prior to instituting full scale phosphorus removal. Without such preliminary testing, excessive time and chemicals could be expended in determining satisfactory operating levels.

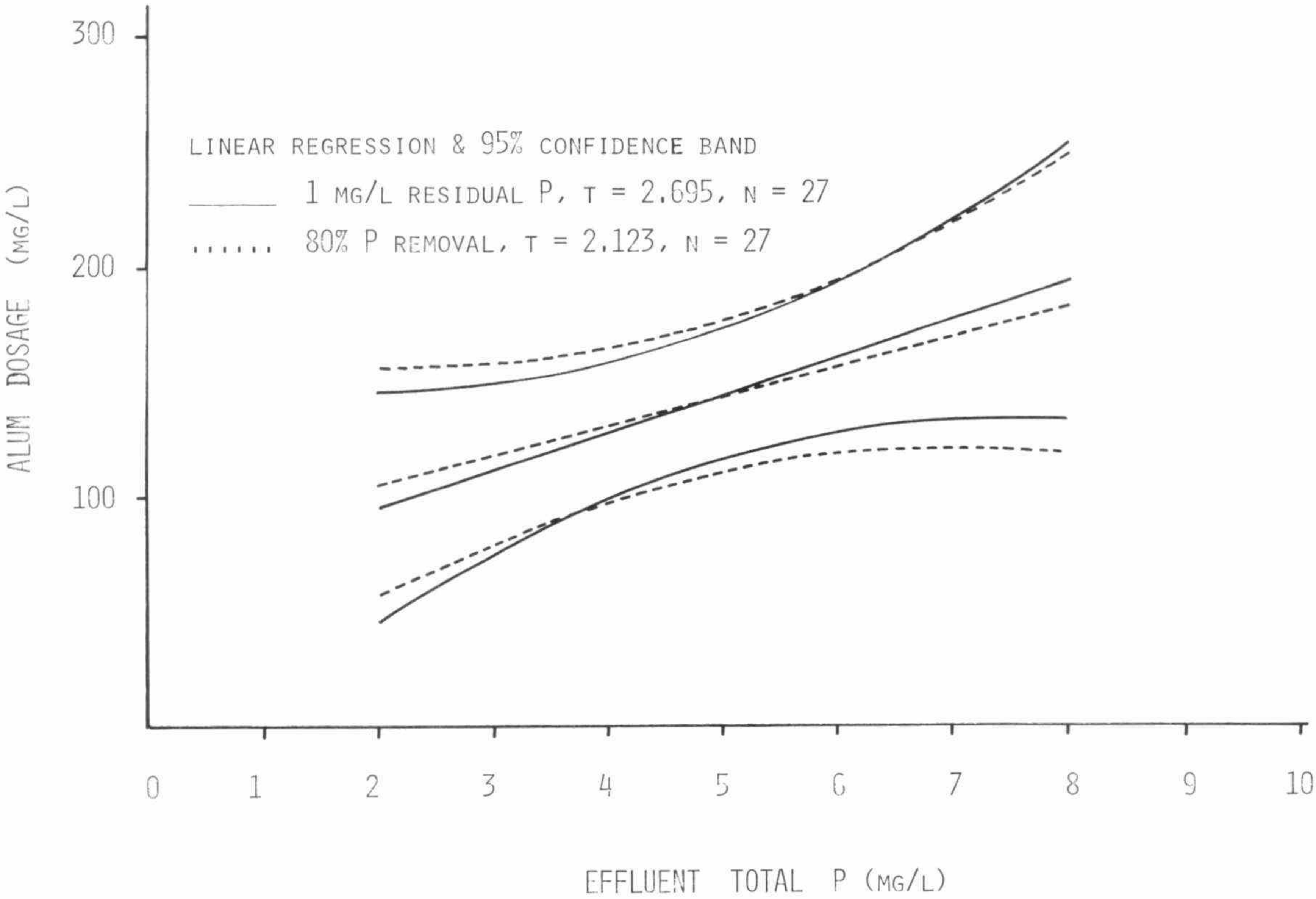

FIGURE 6. P REMOVAL IN FINAL EFFLUENT, ALUM DOSAGE VS TOTAL PHOSPHORUS

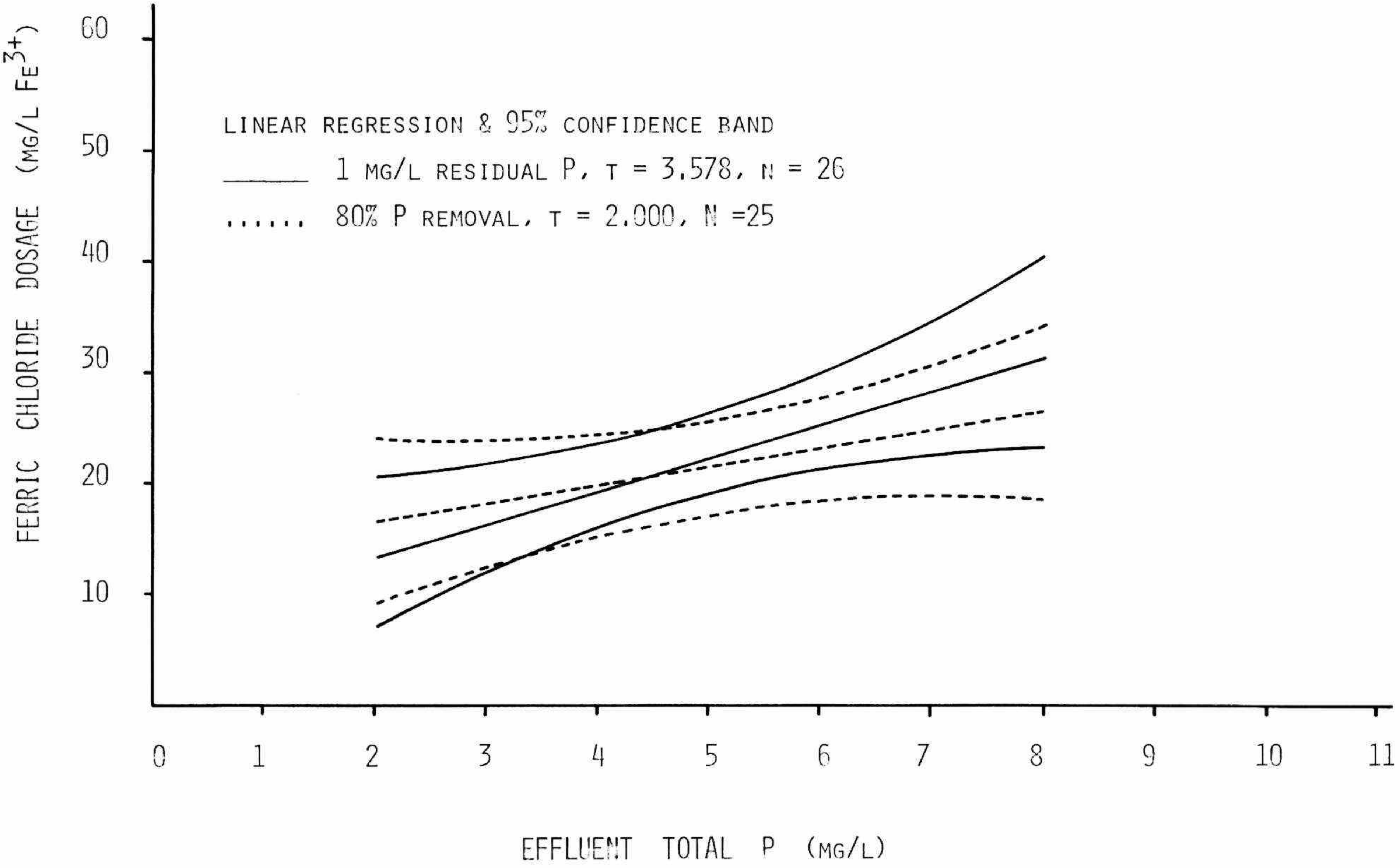

FIGURE 7. P REMOVAL IN FINAL EFFLUENT,
FERRIC CHLORIDE DOSAGE VS TOTAL PHOSPHORUS

The analyses of the raw jar test data indicated that the average total phosphorus in raw sewage for the plants studied was 7.4 mg/l, with the range being 2.3 - 18.0 mg/l. In final effluent, the average total phosphorus concentration was 4.6 mg/l with the observed range being 1.1 - 7.7 mg/l. The average phosphorus removal without chemical addition in WPCP's where jar tests were conducted was 38 percent.

When considering the variability of the jar tests probability plots, the only generalized conclusion that can be drawn from the data analysed is that municipal sewage with a high industrial waste fraction tends to yield more variable performance with respect to phosphorus removal than those of primarily domestic origin. The variability of performance, as indicated by the slope on the probability plots, may aid in selecting which of two chemicals providing phosphorus removal at equal costs should be used for full scale phosphorus removal.

With respect to analysis of jar test data from a specific plant, Figure 8 indicates chemical dosage requirement as a function of raw sewage total phosphorus concentration. The regressions and broad confidence bands shown are typical of jar test results obtained at many municipalities, in that the correlation of dosage and initial phosphorus level is poor and not suitable for chemical addition control purposes.

Possibly a feedback chemical dosage control system based on effluent total phosphorus concentration would be more feasible than the feed forward control system based on influent raw sewage phosphorus level.

In another study supported under the Canada-Ontario Agreement [6], it was concluded that no correlation could be established between the amount of chemical required to achieve 1 mg/l total phosphorus residual and common wastewater parameters.

3.1.4 Lagoon aspects

The nature of preliminary jar testing for phosphorus removal in lagoons will depend on the method of phosphorus removal to be used.

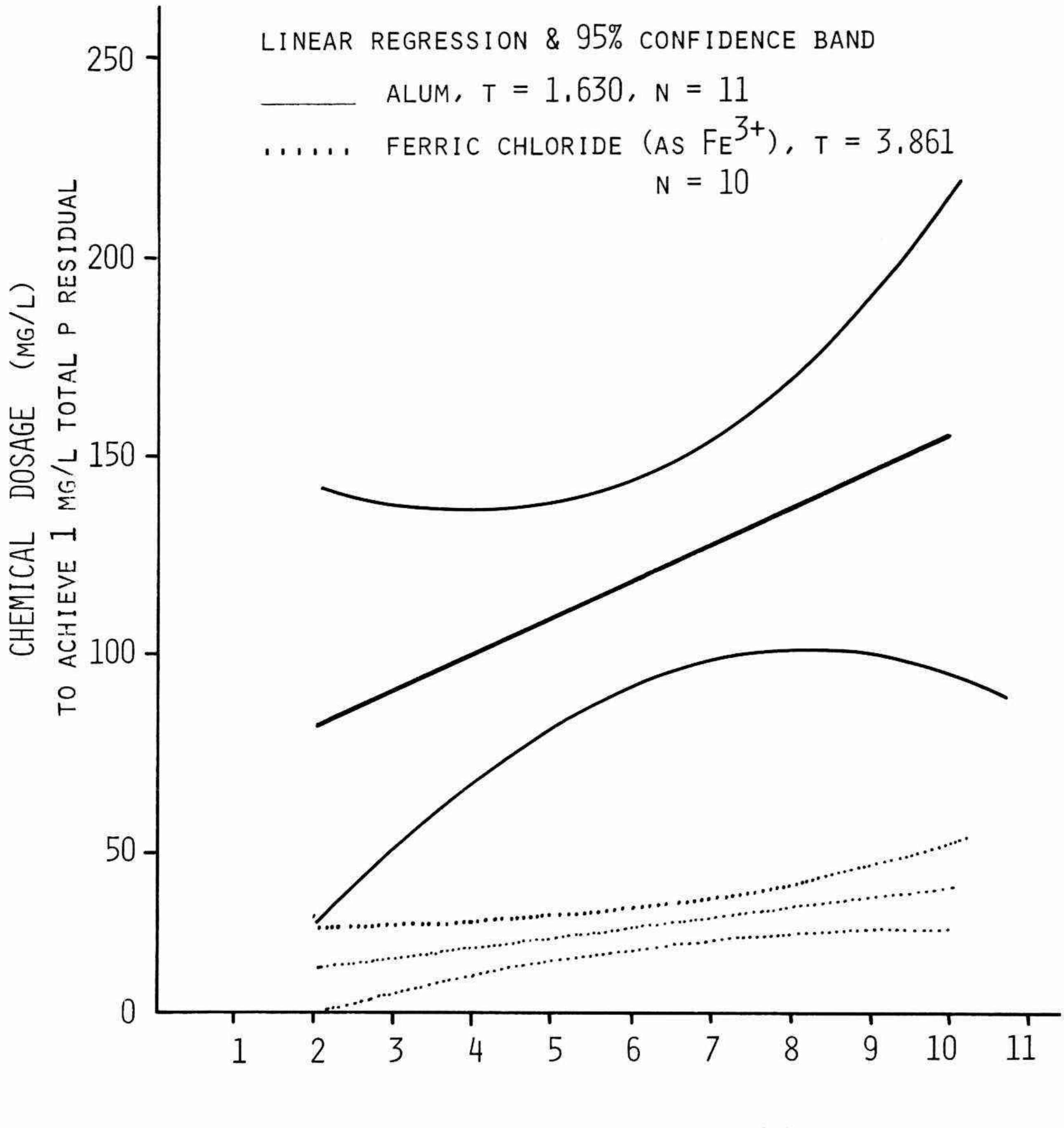

FIGURE 8. DOSAGE REQUIREMENT VS INFLUENT PHOSPHORUS CONCENTRATION, SINGLE PLANT JAR TEST DATA

For continuous chemical addition to raw sewage, jar tests would be conducted in a manner similar to that previously outlined.

When considering batch chemical treatment, jar tests are conducted on lagoon contents. On-site testing is not considered to be essential and limited sampling is adequate because of the long retention period within the stabilization pond, making rapid changes in pond characteristics unlikely. The dosage to be used in the full scale tests should be the one that reduced the phosphorus concentration to approximately 0.5 mg/l. This would allow for possible less efficient field results with the chemical.

3.2 Full Scale Studies

The Canada-Ontario Agreement on the Lower Great Lakes has made $6,000,000 available for both research and treatability studies at municipal WPCP's. These treatability studies [5] involve preliminary testing, as previously outlined, followed by temporary full scale phosphorus removal studies.

The results of preliminary jar tests yield conclusions regarding the optimum chemical for phosphorus removal at a particular WPCP, as well as the general point of application of such a chemical. Full scale studies may then be conducted using this prime coagulant to obtain further information in the following areas:

- chemical dosage;
- point of application;
- sludge characteristics;
- final effluent quality that will be attained;
- preliminary cost data on operating costs related to phosphorus removal;
- suitability of the existing physical plant for phosphorus removal.

Although these full scale studies serve to relate preliminary jar test results to anticipated full scale plant performance, in certain instances full scale studies may not be required or even warranted.

Previous experience, accumulated technical information, and plant, mechanical and process data could all combine to make full scale studies unnecessary.

If full scale tests are to be conducted, it is expected that the studies would be of approximately six weeks duration for a primary treatment plant. For a secondary wastewater treatment plant, eight weeks of full scale operation should yield the required information. Such a study would only involve chemical addition to the waste stream indicated most promising by the jar tests, assuming that addition at this point yielded satisfactory results. Subsequent work in altering the point of application to reduce chemical dosage can be conducted after the full scale facility is permanently on-stream.

An assessment of digester operation during these studies is not considered essential. Flexibility in design of permanent facilities is obviously required.

Under certain circumstances an extended study beyond the time periods previously outlined may be required. The presence of a significant industrial waste load, e.g. cannery wastes, could necessitate more extensive studies both in the jar testing and full scale pilot work.

The prime objective of the full scale temporary phosphorus removal studies is to demonstrate the feasibility of effecting phosphorus removal at a particular installation without necessitating extensive plant modifications or additions. Some of the mechanical plant aspects that may be affected by phosphorus removal are:

- raw sludge collection and handling capability;
- return sludge pumping capacity; and,
- digester heat exchange capacity.

Essentially, the full scale studies should demonstrate that phosphorus removal, using the prime coagulant indicated by the jar tests, is compatible with the existing wastewater treatment processes. While effecting phosphorus removal is the prime objective, the study should not be carried out in a manner which might lead to a deterioration in plant effluent quality.

4. RESEARCH STUDIES

4.1 Mechanical Plants

In order to provide the necessary technical and design information for phosphorus removal implementation, a number of full scale studies were conducted involving the application of the three basic prime coagulants, lime, alum, and ferric chloride, in different types of wastewater treatment facilities commonly encountered in the Province of Ontario. Table 1 summarizes the research studies conducted by outlining the type of wastewater treatment facility, chemical used, point of application, and any additional specific reasons for conducting that particular study.

In order to confirm that the proposed study would be successful at the particular WPCP chosen, preliminary jar tests were conducted according to the method previously outlined. The duration of these full scale studies depends to a great extent on the specific purpose of the study, i.e. where anaerobic digestion is concerned, the studies would be of a minimum six months duration, while an activated sludge process study would be only of two or three months duration.

Although much of the earlier work was conducted using swimming pools as temporary storage tanks, the incidence of problems using such temporary facilities was quite high. Subsequently, five thousand gallon chemical storage FRP tanks were used for these temporary studies. Liquid coagulant was fed through chemical feed pumps either proportional to raw sewage flow or manually adjusted according to diurnal flow variations. During these studies, various in-plant streams were normally sampled three times a week; where digestion studies were involved, sludge samples were obtained on a weekly basis. In addition, the normal operational parameters of both the activated sludge process and anaerobic digestion process were monitored for the duration of the studies.

4.2 Lagoon Studies

In order to allow for complete implementation of the phosphorus removal program, research studies were conducted to determine a means of achieving phosphorus removal in aerated lagoons [20], conventional

TABLE 1. FULL SCALE PHOSPHORUS REMOVAL STUDIES OF MECHANICAL PLANTS

	TYPE & SIZE mgd	REFERENCE	CHEMICAL	POINT OF ADDITION	ADDITIONAL PURPOSE OF STUDY
A)	Conv Act Sl (3.0)	(7)	alum	Raw Aeration	Anaerobic digestion
B)	Conv Act Sl (4.0)	(8)	alum	Raw	Vacuum filter
C)	Conv Act Sl (4.0)	(9)	alum	Raw Aeration	Low alkalinity raw water
D)	Conv Act Sl (0.75)	(10)	alum	Aeration	Anaerobic digestion
E)	Conv Act Sl (2.0)	(11)	lime	Raw	Anaerobic digestion
F)	Conv Act Sl (0.2)	(12)	lime	Raw	High calcium raw water
G)	Conv Act Sl (4.0)	(8)	lime	Raw	Vacuum filter

TABLE 1 Continued

Type & Size mgd	REFERENCE	CHEMICAL	POINT OF ADDITION	ADDITIONAL PURPOSE OF STUDY
H) Conv Act Sl (6.4)	(13)	ferric chloride	Raw Aeration	
I) Conv Act Sl (4.5)	(14)	ferrous sulphate	Raw	Waste pickle liquor, Anaerobic digestion
J) Cont Stab (0.54)	(15)	alum ferric chloride	Contact zone Contact zone	Aerobic digestion
K) Ox Ditch (0.72)	(16)	alum ferric chloride	Raw Raw	Mixing considerations
L) Primary (8.0)	(17)	ferric chloride	Raw	Anaerobic digestion
M) Primary (24.0)	(18)	alum	Raw	Vacuum filter
N) Ext Aer (0.05)	(19)	alum ferrous chloride	Raw Raw	

stabilization ponds, and seasonal retention lagoons [21]. Table 2 summarizes the research studies conducted on such nonmechanical wastewater treatment facilities.

For the study involving phosphorus removal at a facultative aerated lagoon facility, liquid alum was fed to the raw sewage at a nearby pumping station for the initial phase of the study, followed by an attempt to effect phosphorus removal using lime, again fed to the raw sewage at the pumping station. In addition to the liquid phase sampling, close surveillance was made of the depth of sludge in the aeration basins.

Phosphorus removal studies at three conventional waste stabilization pond systems were also conducted; these involved the addition of alum, lime and ferric chloride, respectively, to the raw sewage prior to entering the stabilization ponds. Raw sewage and stabilization pond effluents were sampled weekly and analysed for routine chemical parameters.

Another method of providing phosphorus removal in seasonal retention lagoons is through batch chemical treatment of the pond contents prior to discharge [21]. The method of application for batch treatment is essentially the same with each of the three prime coagulants. The chemical, as a liquid or slurry, is contained in a 150-gallon plastic tank mounted amidships in a 16-foot, 70-HP outboard motorboat. Chemical dispersal throughout the lagoon is by means of a 2-inch syphon discharging into the prop wash.

The study program [21] on this method of phosphorus removal was undertaken to provide information in the following areas:

- feasibility of batch treatment;
- use of alum, lime and ferric chloride;
- large cell application;
- single cell application;
- cumulative effects;
- algal aspects.

TABLE 2. FULL SCALE PHOSPHORUS REMOVAL STUDIES AT NONMECHANICAL PLANTS

TYPE	SIZE OF CELL TREATED (acres)	CHEMICAL	POINT OF ADDITION
Facultative Aerated Lagoon	0.6	lime alum	Pumping station Pumping station
Conv Stab Lagoon	13.2	alum	Pumping station
Conv Stab Lagoon	15	lime	Mix tank prior to entering lagoon
Conv Stab Lagoon	16	ferric chloride	Pumping station
Seasonal Retention Lagoon	5	alum	Lagoon surface

TABLE 2. Continued

TYPE	SIZE OF CELL TREATED (acres)	CHEMICAL	POINT OF ADDITION
Seasonal Retention Lagoon	7	lime	Lagoon surface
Seasonal Retention Lagoon	7	ferric chloride	Lagoon surface
Seasonal Retention Lagoon	15	alum	Lagoon surface
Seasonal Retention Lagoon	17.7	alum	Lagoon surface
Seasonal Retention Lagoon	16	ferric chloride	Lagoon surface

5. RESULTS AND DISCUSSION

5.1 Chemical Aspects

Phosphorus removal by chemical addition to wastewaters has been studied extensively and has been shown to be a viable technique for controlling phosphorus discharges at wastewater treatment facilities. Such removal is essentially effected by transferring both suspended and soluble forms of phosphorus present in the wastewater to the sludge by-product produced in wastewater treatment. This physical/chemical removal takes place through precipitation and adsorption of various phosphates, flocculation of suspended solids, and resultant settling of solids and subsequent removal.

In order to effect phosphorus removal, inorganic coagulants, such as iron or aluminum salts, are added to the untreated wastewater. The multivalent cations of these coagulants combine with the phosphates present to form insoluble precipitates normally remaining in suspension. These metal-phosphate precipitates are small stable colloids requiring further coagulation and flocculation to allow removal from wastewater by conventional sedimentation. Organic and polyphosphate compounds are also removed by a combination of more complex precipitation and adsorption reactions.

The mechanism associated with phosphorus removal by lime addition is considerably different from that resulting from the addition of metallic salts. The formation of insoluble phosphorus compounds when using lime is a pH dependent reaction; as the pH is raised, a compound known as calcium hydroxyapatite is precipitated.

The chemistry of phosphorus removal is considerably complicated by the many competing reactions that can take place; the numerous constituents of wastewater and its varying composition both make a stoichiometric assessment of phosphorus removal a virtual impossibility. The earlier discussion on jar test results is illustrative of the lack of adherance to stoichiometry.

It must be pointed out that any waste product containing appreciable quantities of aluminum, iron, or calcium cations may have potential use for phosphorus removal. Such products could include waste pickle liquors, spent carbide limes, and aluminum finishing wastes. For each situation, however, the suitability must be judged on the basis of content of reactive chemical, continuous availability, uniformity of shipments, and the presence of excessive undesirable contaminants.

5.2 Studies on Mechanical Plants

5.2.1 Process performance

The effluent quality results from the studies carried out in mechanical plants are summarized in Table 3.

In the conventional activated sludge system (A through I in Table 3), the effluent BOD and suspended solids values were similar to those normally associated with this type of treatment system. The total phosphorus reduction was near that predicted by the jar testing program at most of the plants. In some cases, (A, D and I), the dosage required to meet the objectives was somewhat lower than that predicted. This reduced operational dosage is probably the result of recycling accumulated precipitate, thus increasing chemical utilization. The presence of industrial wastes in appreciable quantity had a severe detrimental effect on the ability of the prime coagulant to remove phosphorus. This problem was particularly pronounced when phosphorus removal was effected across the primary clarifier rather than the aeration section. All studies at municipalities receiving significant industrial waste loadings encountered this situation.

In all activated sludge systems where chemical addition to the aeration tank discharge was used to precipitate phosphorus, the hydraulic load on the final clarifier had a marked effect on effluent quality. At hydraulic loads above 750 - 800 gpd/sq ft, a steady deterioration in effluent quality occurred (Figure 9). Final effluent suspended solids values of 25 mg/l were consistently obtained when the hydraulic rate on the clarifiers increased to over 800 gpd/sq ft. Below 800 gpd/sq ft there appears to be no further decrease in effluent suspended solids values. The minimum expected suspended solids value is 10 mg/l from these systems. The effluent BOD values were observed to follow the fluctuations of the effluent suspended solids very closely. With satisfactory solids separation, BOD values of 10 - 15 mg/l were consistently obtained in the studies.

TABLE 3. SUMMARY OF RESULTS IN MECHANICAL PLANTS

PLANT NO.	CHEMICAL & PREDICTED DOSAGE (mg/l)	ACTUAL DOSAGE (mg/l)	POINT OF APPLICATION	EFFLUENT QUALITY					
				TOTAL P		ORTHO P	BOD		SS
				mg/l	% Rem.	mg/l	mg/l	% Rem.	mg/l
A	alum (200)	200	Raw	0.5	96	0.4	7	98	15
		150	Raw	1.2	88	0.8	5	99	15
		100	Raw	1.8	80	1.25	8	98	12
		100	Aeration	1.7	98	0.6	16	97	19
		75	Aeration	2.6	92	0.8	23	96	32
B	alum (150)	150	Raw	1.2	88	1.0	25	81	11
C	alum (125)	125	Raw	1.6	84	0.2	22	88	40
		125	Aeration	1.7	78	0.1	37	82	56
		175	Aeration	0.5	93	0.1	36	81	23
D	alum (175)	131	Aeration	1.3	88	0.4	22	92	24
E	lime (-)	200	Raw	2.0	80	1.8	9	96	7
F	lime (70)	130	Raw	3.1	45	2.2	6	91	13
G	lime (150)	125	Raw	1.8	80	1.6	31	73	6

TABLE 3. Continued

PLANT NO.	CHEMICAL & PREDICTED DOSAGE (mg/l)	ACTUAL DOSAGE (mg/l)	POINT OF APPLICATION	EFFLUENT QUALITY TOTAL P mg/l	% Rem.	ORTHO P mg/l	BOD mg/l	% Rem.	SS mg/l
H	ferric chloride (10 Fe^{3+})	10Fe^{3+}	Raw	0.8	88	0.3	15	87	6
		10Fe^{3+}	Aeration	1.3	80	0.7	15	86	9
I	ferrous sulphate (40 Fe^{2+})	20Fe^{2+}	Raw	3.0	83	2.1	21	88	13
J	alum (125)	125	Contact zone	0.3	94	0.1	3	90	7
	ferric chloride (15 Fe^{3+})	15Fe^{3+}	Contact zone	0.9	88	0.5	9	94	14
K	alum (125)	125	Raw	1.0	80	0.2	17	63	37
	ferric chloride (15 Fe^{3+})	15Fe^{3+}	Raw	0.8	83	0.5	6	91	11

TABLE 3. Continued

PLANT NO.	CHEMICAL & PREDICTED DOSAGE (mg/l)	ACTUAL DOSAGE (mg/l)	POINT OF APPLICATION	EFFLUENT QUALITY					
				TOTAL P		ORTHO P	BOD		SS
				mg/l	% Rem.	mg/l	mg/l	% Rem.	mg/l
L	ferric chloride (15 Fe^{3+})	15Fe^{3+}	Raw	1.2	78	0.5	39	61	33
		15Fe^{3+} 0.5 A-23	Raw	1.3	77	0.7	34	68	26
		20Fe^{3+}	Raw	0.7	85	0.1	37	62	28
		20Fe^{3+} & 0.5 A-23	Raw	0.8	88	0.2	33	67	17
M	alum (100)	100 & 0.4 A-23	Raw	0.5	93	0.1	34	72	20
		90 & 0.4 A-23	Raw	1.0	87	0.4	42	61	30
N	alum (-)	230	Raw	1.5	91	-	14	91	55
	ferrous sulphate (-)	12.5Fe^{2+}	Raw	4.1	68	-	16	89	40
		15 Fe^{2+}	Raw	2.6	86	-	12	94	32

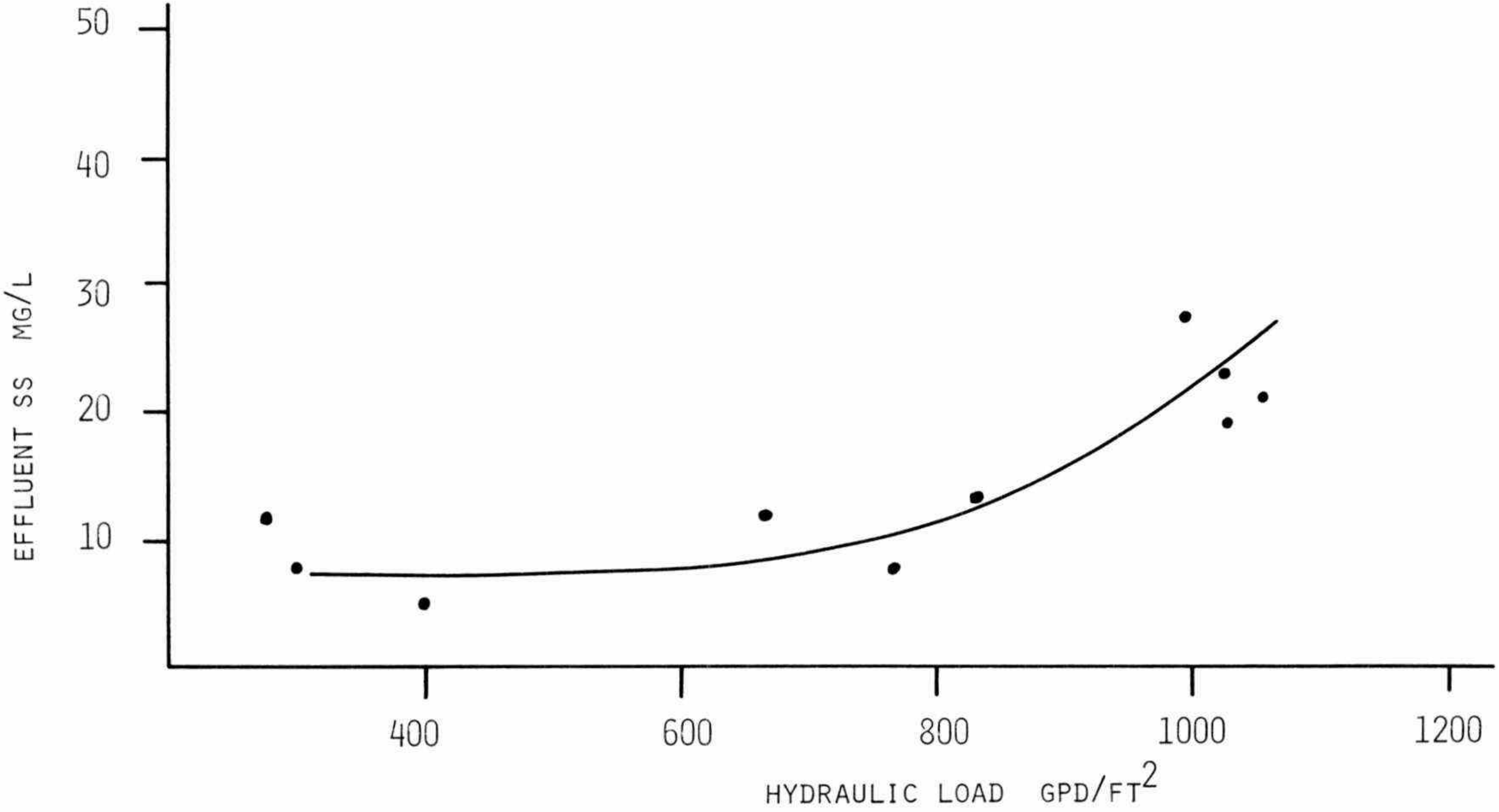

FIGURE 9. EFFECT OF HYDRAULICS,
CHEMICAL ADDITION TO AERATION SECTION

In the operation of full scale plant studies within existing structures, phosphorus removal was readily effected providing adequate mixing of the chemical stream and the wastewater was obtained. In cases where the initial results from the full scale plant study did not approach the jar test predicted results, it was found that either inadequate mixing or excessive hydraulic loadings were the cause. Efficient mixing was obtained in full scale plants in the following ways:

a. chemical injection into the suction side of raw sewage pumps;
b. chemical addition into a pre-aeration tank provided significantly more air can be supplied at the addition point;
c. chemical addition at a Parshall flume or similar constriction in a flow channel;
d. chemical addition into the channel or pipe between the aeration tank and the final clarifier provided additional mechanical agitation or air mixing is available.

In several cases, the phosphorus removal efficiency was doubled by increasing the mixing intensity at the point of chemical addition. The reaction times available in existing plants have normally proven to be adequate. It was found that, by matching the chemical feed rate to the incoming hydraulic load three to eight times/day, adequately consistent results were obtained. No benefit of matching the chemical feed rate to the incoming phosphorus load is expected when considering only the process performance. From an operating cost point of view, it may be advantageous in large plants if a strong correlation is observed.

In plant C, where the effect of alum addition to sewage from a municipality with a low alkalinity raw water was studied, it was found that at acceptable hydraulic rates, alum dosages up to 125 mg/l did not adversely depress the pH. However, at alum dosages of 175 mg/l, the pH was depressed to as low as 3.0 at times. The raw water supply to this municipality has an alkalinity of 10 mg/l as $CaCO_3$ and the raw sewage alkalinity averaged 150 mg/l as $CaCO_3$.

In plant F, jar tests predicted that the addition of 70 mg/l lime to the raw sewage would effect P removal to the desired 1 mg/l level. This sewage is abnormal since it contains a great deal of alkalinity (300 mg/l as $CaCO_3$), and total hardness (950 mg/l as $CaCO_3$). The full scale study was started at the 70 mg/l lime level, but inadequate P removal was experienced. An increase in dosage to 120 mg/l lime did not significantly improve the removal efficiency. Based on raw sewage titration curves, it is anticipated that dosages up to 225 mg/l may be required to effect phosphorus removal.

The use of waste pickle liquor in plant I yielded significantly better results than those predicted by jar tests. The addition of 20 mg/l Fe^{2+} effected in excess of 80 percent total phosphorus removal. Before phosphorus precipitation takes place, the ferrous (Fe^{2+}) ion must be oxidized to the ferric (Fe^{3+}) ion. This oxidation requires approximately 0.15 lb O_2/lb Fe^{2+}. The reaction rate in sewage, however, is fairly slow, with more than two hours aeration required to oxidize most of the Fe^{2+} to Fe^{3+}. Thus, it is not feasible to use waste ferrous iron sources for phosphorus removal in primary treatment plants even if a pre-aeration tank is available for partial oxidation of the iron. No deterioration in effluent quality was noted; however, a gradual increase in digested sludge heavy metal content was observed, although there were no digester operating problems during the ten months of the study.

In the contact stabilization study, high quality effluent was consistently obtained. No change in aerobic digester operation was noted.

Satisfactory effluent quality and no solids deposition within the ditch resulted from the addition of alum or ferric chloride to the oxidation ditch wastewater treatment plant.

The use of alum and ferrous chloride in a conventional extended aeration plant produced a poor effluent quality. The high effluent SS values were thought to be attributable to the location of chemical addition, i.e., to the raw sewage. It has been speculated that significantly better operation could have been obtained by adding the chemicals to the discharge of the aeration tanks.

When alum and ferric chloride are added to the aeration section of a secondary plant, the allowable clarifier hydraulic loading appears to be related to the point of chemical addition. With ferric chloride addition, better clarifier performance was observed when the chemical was added at the influent end of the aeration section; in contrast, with alum addition, better performance was observed with chemical addition at the effluent end of the aeration section.

In plants E, F and G, the orthophosphorus level consistently increased from the primary effluent to the final effluent. This increase is likely due to a resolubilization of lime floc carried into the neutral pH regime of the aeration tank. Because of this resolubilization and corresponding high soluble phosphorus concentration, it will likely be difficult to obtain a 1.0 mg/l total phosphorus residual in the final effluent. When working within existing plants, without major capital addition, it is likely that lime will provide a 1.5 - 2.0 mg/l total phosphorus effluent. To attain higher quality effluents, major capital expenditures may be required.

In some cases, the addition of alum to an activated sludge process partially inhibited nitrification. To ensure complete nitrification, it may be necessary to change operating conditions, i.e., increasing sludge age.

5.2.2 Sludge production

In phosphorus removal studies to date, the sludge production and characterization has produced relatively consistent results.

A. Metal Salts. In secondary plants using metal salts, the pounds dry solids produced per million gallons of waste treated generally increased by 5 - 25 percent. The production rate during phosphorus removal varied from 2000 - 3300 lb dry solids/MG treated. In addition to this increase in sludge mass, there was a decrease in solids concentration in the raw sludge, dropping the total solids content to 3.5 - 5.0 percent from the normal 4.0 - 5.5 percent. The combination of these two effects, both tending to increase the wet sludge volume by approximately 35 percent, has resulted in several digester operating problems discussed in the next section.

In primary plants, the sludge production increased more drastically as a result of the increased solids capture. A 100 percent increase in lb solids produced/MG can be expected. Depending upon the raw waste characteristics, the solids production varied from 1500 - 2500 lb solids/MG with phosphorus removal, from a normal 700 - 1200 lb/MG. The majority of this increased production can be attributed directly to the increase in solids capture. A 20 percent reduction in sludge solids concentration can be expected. The net effect on sludge volume was a 150 percent increase.

B. Lime. The use of lime for phosphorus removal in secondary plants produced several very marked changes in both sludge characteristics and sludge production. The sludge production increased from 1800 lb/MG to 4600 lb/MG with the addition of 200 mg/l lime, while the solids content of the sludge increased from a normal 4.5 percent to 9 percent. The net effect was a 25 percent increase in sludge volume to be handled.

With lime addition at a primary plant, the effects were even more dramatic. The sludge production increased from a normal of 800 lb/MG to 2400 lb/MG. The solids concentration increased to 15 percent from the norm of 7 percent. The net effect was a 50 percent increase in sludge volume.

5.2.3 Sludge digestion, dewatering and disposal

Because of the predominance of anaerobic digestion systems in the Province of Ontario, emphasis was placed on assessing the impact of phosphorus removal on this particular sludge treatment process, rather than heat treatment or incineration. Table 4 summarizes the steady state data collected from the digestion studies during phosphorus removal.

In all cases where metallic salts were used to precipitate phosphorus, normal digestion process operation was observed. However, some problems were experienced during these studies due to inadequate heat exchanger capacity, caused by increased digester hydraulic loading and high gas production rates, resulting in inadequate gas-liquid separation and foaming in the primary digester.

TABLE 4. ANAEROBIC DIGESTION OF CHEMICAL SLUDGES

PLANT:	L	A	D	E
Raw Sludge				
% solids	4.36	3.8	7.5	10
% volatile solids	54.5	66	43	27
Digested Sludge				
% solids	16	3	5.9	8
% volatile solids	39.4	54	37.6	25
ortho P (mg/l)	1.9	0.5-19	6-19.9	4
Supernatant				
% solids	0.17	NA	5.6	1.2
pH range	6.8-7.0	NA	7-7.3	7.5-8.0

TABLE 4. Continued

PLANT:	L	A	D	E
Gas production (cu ft/day)	NA	32,800	8,029	NA
% reduction of vol. solids	45	39.5	18	19
Primary digestion loading (lb vol/ft^3/d)	0.04	0.1	0.054	0.108
Overall digester loading (lb vol/ft^3/d)	0.03	0.04	0.054	0.05
Gas analyses	good burning	30% CO_2 70% methane	35% CO_2 65% methane	24% CO_2 76% methane
Chemical used	Ferric Chloride	Alum	Alum	Lime

These problems did not arise as a direct result of chemical addition, but were compounded by the increased volatile solids load on the digestion system. No inhibitive effect from the accumulated metal salts was observed in any of the digesters studied, nor was a significant portion of the phosphorus resolubilized during the digestion process. Even the digester treating phosphate sludge from precipitation with the ferrous sulphate waste pickle liquor showed only 8.0 mg/l orthophosphorus in the digester contents.

The digester treating sludge resulting from precipitation using lime in raw sewage encountered several operational problems early in the research study. Erratic lime dosing resulted in periodic massive doses of high pH sludge being pumped to the digester, causing the digester pH to rise drastically. After three months of operation, gas production ceased and the cover had to be opened to allow sludge removal. Subsequent studies showed that, if the raw sludge was held for an extended period in the primary clarifier, it partially neutralized itself to approximately pH 8.0, allowing proper operation of the anaerobic digester system. Table 4 shows normal operation which had been maintained for seventeen months [11]. The only significant change from normal operation was the high solids content of the digested sludge.

Table 5 summarizes the operational results of the use of full scale vacuum filters for the dewatering of raw undigested chemical sludges from both primary and secondary plants [8, 18].

A significant increase in conditioning costs was experienced with alum addition to the primary plant. A decrease in cake solids content and filter yield was also noted.

In the secondary plant, little change took place upon alum addition. The addition of lime resulted in a reduction in conditioning costs and an increase in filter yield and sludge cake solids.

Raw sludge from a conventional secondary plant using lime coagulation of the raw sewage was dewatered using a continuous solid bowl conveyor-type centrifuge [22]. In excess of 95 percent solids capture was obtained using less than 1.0 lb anionic polymer/ton of dry solids; sludge cake solids of 25 - 30 percent by weight were obtained when treating five percent total solids sludge. Centrate solids of less than

TABLE 5. VACUUM FILTRATION OF CHEMICAL SLUDGES

(normal operation in brackets)

Plant (Table 1)	G	B	M
Type of sludge	Lime	Alum	Alum
Filter Yield lb solids/sq ft/hr	7.2 (5.2)	4.6 (5.2)	5.8 (11.3)
Conditioning Chemicals			
% lime	9.9 (15)	17.9 (15)	27.9 (6.9)
% $FeCl_3$	4.3 (4.5)	5.4 (4.5)	1.1 (1.1)
Costs $/ton	11.14 (16.08)	17.96 (16.08)	9.50 (3.10)
Cake % dry solids	29	15.9	19.2 (31.1)
Filtrate SS mg/l	-	9630	6810 (2660)
Type of Plant	Secondary	Secondary	Primary

1000 mg/l were consistently obtained. Centrifugation without polymer addition resulted in lower solids capture at similar cake and centrate solids levels.

The most common method of sewage sludge disposal in Ontario is land application of liquid sludge. The stabilized sludge is transported by tank truck and spread thinly on the land [23, 24]. Of necessity, studies involving the effect of chemical sludges on the growth of agricultural products require a period of several years to draw any firm conclusions. A number of studies, funded under the Canada-Ontario Agreement, have been undertaken to investigate the effect of land application of sewage sludge on crop yield and contamination of soil, crop, and surface and groundwater.

5.3 Studies on Nonmechanical Plants

The phosphorus removal study on the facultative aerated lagoon facility was unsuccessful. Total phosphorus removals averaged only 45 percent with an effluent total phosphorus concentration of 3.0 mg/l. In addition, sludge accumulation within the aerated cells was so excessive as to make phosphorus removal within an aerated lagoon facility impractical. Sludge accumulations of 1 - 1.5 inches/month were measured for a six-month period. Although effluent soluble phosphorus concentrations were very low (0.2 mg/l), high suspended solids content (100 mg/l) in the aeration cell effluent made it impossible to achieve low total phosphorus concentrations in the cell discharge. It was not possible to determine whether the high suspended solids in the aeration cells were the result of poor flocculation characteristics or whether excessive aerator mixing conditions were causing resuspension of chemical floc. As most facultative aerated lagoon facilities in the Province of Ontario are followed by conventional stabilization ponds, it appears that the only means of providing phosphorus removal at such wastewater treatment facilities would be direct chemical addition to the aeration cell effluent prior to entering the stabilization pond.

The studies involving continuous chemical addition, using alum, ferric chloride, or lime, to raw sewage entering conventional waste stabilization ponds were of approximately two years' duration. While the continuous alum and ferric chloride studies were successful in phosphorus reduction to well below the 1.0 mg/l objective, the average phosphorus concentration in the lime study lagoon effluent was 1.9 mg/l, with a range of 0.8 to 2.7 mg/l total phosphorus. Average orthophosphorus concentrations in the three studies were 0.08, 0.06 and 1.2 mg/l for the ferric chloride, alum and lime studies, respectively. Little or no effect was observed on other effluent quality parameters such as BOD and SS [25].

Batch chemical treatment of seasonal retention stabilization ponds using alum and ferric chloride was highly successful. Effluent quality after treatment was usually less than 10 mg/l BOD and 20 mg/l SS, 0.5 mg/l total phosphorus, and 0.3 mg/l soluble phosphorus. Lagoon emptying was usually initiated the day after treatment. Due to a slight deterioration in effluent quality after two weeks, it was desirable to complete the discharge of the pond contents within eight to ten days after treatment.

The main application objectives in lagoon batch treatment are rapid even distribution of the chemical and good mixing action. Labour requirements for batch treatment with a liquid chemical would be 1.5 - 2.0 man-hours per acre per treatment [21].

Algal blooms in the continuous feed studies were observed to affect effluent phosphorus levels over a relatively long time, whereas with batch treatment, the time of discharge was very short and the effects of algae on effluent quality were less of a problem.

5.4 Post-Secondary Treatment

While phosphorus removal providing an effluent containing less than 1.0 mg/l phosphorus can be achieved using the previously outlined methods, post-secondary treatment becomes necessary if more stringent effluent quality and lower phosphorus levels are required. Effluent total phosphorus levels in the order of 0.1 to 0.5 mg/l, and BOD values less than 10 mg/l, can be expected from post-secondary treatment processes [26].

As expected, this further treatment requires the addition of separate equipment to the existing secondary plant. Most of this equipment and the design criteria are drawn from the water treatment field.

This discussion on post-secondary treatment is limited to chemical addition and its required flash mixing, flocculation, clarification, and filtration. Although chemical addition may yield good additional phosphorus removal, filtration is usually added to remove any carryover floc and thus yield total phosphorus residuals as low as 0.1 mg/l.

Usually lime or alum are used as the chemical coagulants. Iron salts are seldom used because of the potential colouring effect that the iron dosage may have on the final effluent. Again, jar tests will indicate the choice of coagulant to be used. Detailed process criteria covering flash mixing requirements, flocculator design, and clarifier considerations are presented in reference 26.

When lime is used in this type of treatment, high dosages are required to achieve the pH of 11.0 - 11.5 required for low phosphorus residuals. This necessitates further readjustment of pH prior to filtration or discharge to the receiving water. Commercial CO_2 or flue gas is normally used as the source of carbon dioxide to effect recarbonation.

When low phosphorus residuals are required, a simultaneous demand is usually made for extremely high quality effluents with respect to other parameters such as BOD and SS. Final filtration of the effluent before discharge is then necessary to provide the degree of treatment required and is also essential to provide a consistent effluent quality. Rapid sand and mix-media type of filters appear to be most applicable for such effluent polishing.

6. CONCLUSIONS

1. A satisfactory predictive technique has been developed which allows rational selection of a prime coagulant for phosphorus removal at a particular WPCP.

2. Phosphorus removal was readily implemented with minimal capital expenditure at all municipal WPCP's studied.

3. Satisfactory effluent quality was attained by the activated sludge process and its modifications when phosphorus removal was practised. Increased sludge production was experienced in all systems, with the sludge quality and quantity dependent upon the chemical used for phosphorus removal.

4. Anaerobic digestion of chemical sludges associated with phosphorus removal was successful; no significant phosphorus release was observed during anaerobic digestion.

5. Two feasible methods of providing phosphorus removal at stabilization ponds have been developed, either continuous chemical feed or batch chemical treatment of pond contents.

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